Fall 11-13-1998

A Statistical Treatment of the Gamma-Ray Burst "No Host Galaxy" Problem: II. Energies of Standard Candle Bursts

Dieter H. Hartmann
Department of Physics and Astronomy, Clemson University, hdieter@clemson.edu

David L. Band
CASS, UC San Diego

Bradley E. Schaefer
Department of Physics, Yale University

A STATISTICAL TREATMENT OF THE GAMMA-RAY BURST "NO HOST GALAXY" PROBLEM: II. ENERGIES OF STANDARD CANDLE BURSTS

David L. Band
CASS 0424, University of California, San Diego, La Jolla, CA 92093; dband@ucsd.edu

Dieter H. Hartmann
Department of Physics and Astronomy, Kinard Laboratory of Physics, Clemson University, Clemson, SC 29634; hartmann@grb.phys.clemson.edu

Bradley E. Schaefer
Department of Physics, Yale University, New Haven, CT 06520; schaefer@grb2.physics.yale.edu

Received 1998 July 8; accepted 1998 November 6
To appear in the 1999 April 1 issue of
The Astrophysical Journal (volume **514**)

ABSTRACT

With the discovery that the afterglows after some bursts are coincident with faint galaxies, the search for host galaxies is no longer a test of whether bursts are at cosmological distances, but rather a test of particular cosmological models. The methodology we developed to investigate the original "no host galaxy" problem is equally valid for testing different cosmological models, and is applicable to the galaxies coincident with optical transients. We apply this methodology to a family of models where we vary the total energy of standard candle bursts. We find that total isotropic energies of $E < 2 \times 10^{52}$ erg are ruled out while $E \sim 10^{53}$ erg is favored.

Subject headings: gamma-rays: bursts—methods: statistical

1. INTRODUCTION

The absence of the host galaxies expected under the simplest "minimal" cosmological gamma-ray burst model was first advanced as a challenge to the cosmological hypothesis of burst origin (Schaefer 1992), but with the evidence from the recently-discovered optical transients (OTs) that some, and probably all, bursts are at cosmological distances, the search for host galaxies is now a tool for learning where bursts occur. The minimal model assumed that bursts are standard candles which did not evolve and that they occur in galaxies at a rate proportional to the galaxy luminosity (e.g., Fenimore et al. 1993). Because of a dispute as to whether there was indeed a "no-host" problem for the minimal model (Larson & McLean 1997), we developed a statistical methodology which compares the hypotheses that host galaxies are or are not present (Band & Hartmann 1998, henceforth Paper I). This methodology clearly demonstrated the obvious point that one can only test a well-defined model. A preliminary application of this methodology showed that the galaxies predicted by the minimal cosmological model were indeed absent.

As a result of the galaxies coincident with the OTs, and the magnitudes and redshifts of these galaxies, there is little doubt that some (and by Occam's Razor, probably all) bursts are cosmological but the minimal cosmological model is clearly too simple. The methodology we developed tests a particular cosmological model against the hypothesis that the host galaxies predicted by this model are not present; this methodology can be generalized to compare different models. The methodology includes a finite-sized "error box" for the particular burst under investigation, which would seem to be inappropriate for bursts followed by OTs whose positions are known exceedingly well. However, the error box actually consists of the burst localization uncertainty and the model-dependent region around the host galaxy in which the burst is expected to occur. For example, some models may require the burst to occur at the center of the host galaxy (e.g., a flare by an otherwise dormant AGN) while other models may permit bursts to occur in an extended halo surrounding the host galaxy.

In this paper we make the simplest modification to the minimal model. Bursts are still standard candles which occur in galaxies at a rate proportional to the galaxy's luminosity, but we vary the intrinsic brightness of the standard candle. Such a model would be consistent with the observed burst intensity distribution only if the source density is allowed to evolve (Fenimore & Bloom 1995). Because of the redshift associated with GRB 970508 (Metzger et al. 1997), the source models in which the death of a massive (therefore short-lived) star gives birth to the burst progenitor (e.g., a neutron star), and the implications of the host galaxy issue, a model as been proposed where the burst rate is proportional to the cosmic star formation rate (Totani 1997; Wijers et al. 1998; Hartmann & Band 1998; Krumholtz, Thorsett & Harrison 1998; Che, Yang & Nemiroff 1998). In these new cosmological models, bursts occur at greater redshifts, and consequently their intrinsic brightness must increase. Here we determine what intrinsic brightness is consistent with the host galaxy observations. Bursts are standard candles in the model we study, which is clearly not the case, as shown by Table 1. In Table 1 we include GRB 980425, even though this burst, associated with a peculiar supernova (Galama et al. 1998), is most likely from a population different from most bursts. In future studies we will include luminosity functions in our analysis. Nonetheless, the analysis here demonstrates decisively that the average burst energy is much greater than previously thought.

Based on some of the same data we use here, Schaefer (1998) also concludes that if bursts are in galaxies, then they must intrinsically be two orders of magnitude brighter than predicted by the minimal model. Schaefer calculates the fraction of the model-dependent host galaxy distribution which is fainter than the brightest observed galaxy; if only host galaxies are present, then the average of this fraction should be 1/2 if the host galaxy model is correct. To compensate for the presence of unrelated background galaxies, Schaefer weights this fraction for each burst based on the brightness ratio of the expected host and background galaxies.

Since the statistical methodology is derived in Paper 1, here we only review the basic formulae (§2.1). Because many of the cosmological models push the host galaxies out to higher redshifts, we can no longer rely on the Euclidean r^{-2} law to relate the intrinsic and observed galaxy brightnesses, but we must include both k- (spectrum redshifting) and e- (evolution) corrections; the sources of our astronomical data are presented in (§2.2). In §3 we analyze different datasets, and discuss the results in §4.

2. METHODOLOGY

2.1. The Likelihood Ratio

In Paper I we presented a Bayesian odds ratio which compares the hypothesis $H_{\rm hg}$ that both host galaxies of a specific cosmological model and unrelated background galaxies are present in burst error boxes to the hypothesis $H_{\rm bg}$ that only background galaxies are present. The odds ratio for a set of N bursts

$$O_{\rm hg,bg} = \frac{p(H_{\rm hg})}{p(H_{\rm bg})} \prod_{i=1}^{N} \frac{p(D_i \,|\, H_{\rm hg})}{p(D_i \,|\, H_{\rm bg})} \tag{1}$$

consists of two factors. The first is the ratio $p(H_{\rm hg})/p(H_{\rm bg})$ of the "priors," the probabilities that each hypothesis is correct, evaluated before the new data were acquired. The second is the "Bayes" factor $\prod p(D_i \,|\, H_{\rm hg})/p(D_i \,|\, H_{\rm bg})$, the ratio of the likelihoods for each hypothesis. The expression D_i represents the observed data for the ith burst, and thus $p(D_i \,|\, H_x)$ is the probability of observing D_i if hypothesis H_x is true. In general, we set the priors ratio to 1, and therefore the odds ratio is the likelihood ratio.

The odds ratio $O_{\rm hg,bg}$ tests whether the host galaxies predicted by a particular model are present. We can compare different models by forming odds ratios which compare these models; these odds ratios would be the ratios of $O_{\rm hg,bg}$ evaluated for each model. Equivalently, we evaluate $O_{\rm hg,bg}$ for each model, and then compare the resulting values. We want not only the best model, but a model for which the host galaxies are clearly present (which requires $O_{\rm hg,bg} > 1$). Here the models are defined by the value of the total burst energy, and therefore our primary objective is an exercise in parameter estimation. Typically for parameter estimation we maximize the likelihood for the desired parameter weighted by the prior for that parameter. The likelihood is the numerator of the Bayes factor, i.e., $\prod p(D_i \,|\, H_{\rm hg})$. If we use a uniform prior for the total burst energy (i.e., we assume that any value of the energy is equally probable *a priori*), then this likelihood is proportional to the odds ratio (eq. 1). Therefore maximizing the odds ratio will give the best estimate of the total energy. By using the odds ratio we also demonstrate that the host galaxy model with this best estimate of the total energy is acceptable.

For this analysis there are two types of bursts. First are the bursts which are localized by their gamma-ray emission (e.g., by an Interplanetary Network or the *Beppo-SAX* WFC), or their X-ray afterglow (e.g., by the *Beppo-SAX* NFI). The error boxes are dominated by the localization uncertainty and range in size from a fraction to tens of square arcminutes; these are the error boxes which traditionally have been searched for host galaxies. The second category consists of the bursts followed by OTs for which the burst positions are presumably known to a fraction of an arcsecond. For these bursts the localization uncertainty is small, and the region of the sky permitted by the cosmological model may dominate the error box. This study shows that the bursts of the first group place firm lower limits on the burst intensity while the second group selects a favored range of burst intensities. Ultimately the observations of the second burst group will be the most constraining, yet we will continue to include the first group for completeness and consistency.

The overall likelihood ratio is the product of the likelihood ratios for each burst. Assume that a given error box is observed down to a limiting flux $f_{\rm lim}(\Omega)$, where we can allow this limit to vary over the error box; Ω represents the spatial coordinates. These observations detect n_d galaxies, each with a flux f_i located at Ω_i. Let the distribution of background galaxies be $\phi(f)$ (number per flux per angular area) and the burster's host galaxy is drawn from the model-dependent distribution $\Psi(f)$, which must be normalized to 1 (when integrated over the flux) since there can only be one host galaxy per error box. The burst localization uncertainty and the host galaxy model result in a probability density $\rho(\Omega)$ for the host galaxy's position on the sky; ρ is also normalized to 1. Both Ψ and ρ represent the cosmological model being tested.

The likelihood ratio for one error box is

$$\frac{p(D_i \mid H_{\rm hg})}{p(D_i \mid H_{\rm bg})} = \int d\Omega \int_0^{f_{\rm lim}(\Omega)} df\, \Psi(f)\rho(\Omega) + \sum_{j=1}^{n_d} \frac{\Psi(f_j)\rho(\Omega_j)}{\phi(f_j)} \quad . \tag{2}$$

This expression was calculated by breaking the three dimensional space of f and Ω into little bins, evaluating the probabilities of obtaining the observed data (galaxies in a few bins and no galaxies in all the other bins), and then letting the bin dimensions go to zero.

The likelihood ratio in eq. (2) assumes the redshifts of the detected galaxies are unknown. When the redshift is known then both Ψ and ϕ in the last term in eq. (2) gain a redshift dependence. Of course, some models (e.g., bursts where the intensity is a standard candle) may give a value of $\Psi = 0$ for a particular redshift. Redshift information will be considered in a future study.

2.2. Data

This analysis requires various observed distributions in a variety of different optical bands. Here we summarize our data sources.

The background galaxy distribution ϕ is derived from galaxy counts. We parameterized the $\rm b_j$, R and K distributions using Figure 2 of Koo & Kron (1992) which summarizes the observations from a number of studies. The $\rm b_j$ and R distributions agree with the study of Jones et al. (1991) while the R band distribution from Smail et al. (1995) is a bit higher than the Koo & Kron (1992) distribution. The V and I band distributions are from Smail et al. (1995), and the U band from Jones et al. (1991). In all cases we extended the galaxy distribution as a power law beyond the data presented in these sources.

The host galaxy distribution $\Psi(f)$ is model-dependent. This model consists of two components: the distribution of likely redshifts for a given burst, and the distribution of host galaxy brightnesses at a given redshift. In this study we assume bursts are standard candles whose brightness does not evolve, resulting in a unique mapping between the burst intensity and its redshift. In future studies we will consider bursts with luminosity functions which evolve in time; a luminosity function with a finite width gives a burst a range of possible redshifts. The host galaxy distribution at a given redshift is also model-dependent: the burst rate may be constant per galaxy (e.g., Brainerd 1994) or may be proportional to the galaxy mass (e.g., Fenimore et al. 1993). In many of these models the host galaxy distribution is the regular galaxy distribution weighted by a power of the luminosity. Here we will assume that the burst rate is proportional to a galaxy's luminosity, and therefore we weight the galaxy distribution by the luminosity. We approximate the regular galaxy distribution by a Schechter function (Peebles 1993, p. 120),

$$\psi(y) = \psi_0 y^\alpha e^{-y} \quad , \tag{3}$$

where $y = L/L_* = f/f_*$. The intensity scale L_* is typically measured as the absolute magnitude in a given spectral band. As described in Paper I, we use $M_* = -19.72$ from Ratcliffe et al. (1997) for the $\mathrm{b_j}$ band, $M_* = -23.12$ from Gardner et al. (1997) for the K-band, and $M_* = -20.29$ from Lin et al. (1996) for the R-band. The index α is usually of order -1, and for computational ease we use $\alpha = -1$. We used standard galaxy colors to interpolate the values of M_* to other optical bands. Since M_* is derived from observations of magnitude vs. redshift, to all these expressions for M_* should be added an additional term $5 \log h$, where $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$, resulting from the uncertainty in Hubble's Constant H_0; however, this dependence on the value of H_0 is cancelled by the H_0 dependence in the relationship between z and the host galaxy flux, and therefore we do not include the dependence on h. Care must be taken that the same normalizing value of H_0 was used throughout. In calculating the observed flux for galaxies with redshifts of more than a few tenths we need both k-corrections for the shift in spectrum and e-corrections for the evolution of the galaxy's luminosity and colors. Therefore

$$m_* = M_* + 5 \log[3 \times 10^8 z \xi(z; q_0)] + K(z) + E(z) \ , \qquad f_*(z) = f_0 10^{-0.4 m_*} \ , \tag{4}$$

where f_0 is the normalizing flux (i.e., the flux of a 0 magnitude object) for a given band, and $K(z)$ and $E(z)$ are the appropriate k and e-corrections. This expression assumes that M_* was provided for $h = 100$. The dependence on $q_0 = \frac{1}{2}\Omega_0 - \Lambda_0$ is $\xi(z; q_0) = 1/q_0 + (q_0 - 1)(\sqrt{1 + 2q_0 z} - 1)/z q_0^2$ (Mattig 1958).

We use the k- and e-corrections of Fioc & Rocca-Volmerange (1997) provided in the compendium of Leitherer et al. (1996). These corrections are given for a large number of filters by galaxy type as a function of redshift for 3 different cosmologies—(H_0, Ω_0 and Λ_0)=(50, 0.1, 0.0), (50, 1.0, 0.0) and (75, 0.1, 0.9); in our calculations we use the first cosmology. We use a galaxy mix based on Ellis (1983) to calculate a k- and e-correction for an average L_* galaxy. Using a host galaxy model which is a weighted average of the Schechter functions for each galaxy type would be more accurate than using a Schechter function based on an L_* with average k- and e-corrections, but as we show below, the k- and e-corrections change the value of the odds ratio but not the burst energy at which it peaks.

3. RESULTS

We apply our methodology to two observational databases. The first is the compendium of Schaefer et al. (1998) which describes 23 error boxes from before 1997 (the compendium also includes 3 of the bursts localized by *Beppo-SAX*, but we treat these bursts separately). The compendium provides the multiband magnitudes of the brightest galaxy in the error box (except for GRB 790307, for which there is only an upper limit); since the flux is provided for only the brightest galaxy in the error box, this flux is also used as the detection threshold. Except where otherwise indicated, these magnitudes are "corrected" for Galactic extinction using the Galactic latitude λ: the extinction in band x is assumed to be $A_x = C_x(\csc(\lambda) - 1)$ where C_x is a constant. The sizes of the error boxes, as well as the bursts' energy fluences, are also taken from Schaefer et al. (1998). We call this database the "Schaefer Compendium."

The second database consists of the recent bursts through GRB 980703 which were followed by OTs. We do not include GRB 980425 which appears to have originated in a supernova in a nearby galaxy (Galama et al. 1998). If this burst is indeed associated with the supernova, the energy requirements differ radically from other bursts (see Table 1); in addition, no other bursts have had nearby galaxies with supernovae in their error boxes. Therefore we suspect that either GRB 980425 is a member of a rare burst population, or the association with the supernova is spurious. Thus this database is a complete sample of bursts which are followed by OTs. The bursts we use are listed by Table 2, which includes the references for the observations. Most observations are initially reported by IAU circulars or by circulars distributed by the GRB Coordinates Network (GCN—Barthelmy et al. 1998). All the OTs were coincident with an extended or persistent source which we take to be the host galaxy. We assume that the error box, the sum of the uncertainty in the position of the OT and the model-dependent region around the galaxy in which we expect the OT, has a radius of $1''$. In the future we will use more detailed models for the distance between the burst progenitor and the galaxy.

In this study the standard candle is the total energy released, which we observe as the energy fluence. The fluences for the Schaefer compendium are for $E > 20$ keV while the fluences for the OT database are predominantly the BATSE $E = 25$–2000 keV fluences; in the absence of additional spectral information, we treat both fluence types as bolometric. Bursts are clearly not standard candles, as is clear from the isotropic energies calculated for GRB 970508, GRB 971214 and GRB 980703 which differ by a factor of ~ 40. Therefore in this study we do not use the redshift information (as will be discussed in a future paper, redshift information can be incorporated into our methodology only for burst models with luminosity functions which allow the burst to have occurred at a range of redshifts for a given observed brightness). Because we use the k- and e-correction model for (H_0, Ω_0 and Λ_0)=(50, 0.1, 0.0), we use the same cosmological model in calculating the total energy from the energy fluence, although we find that varying Hubble's constant does not alter the qualitative results.

To reiterate, the burst model which we investigate assumes bursts occur in galaxies at a rate proportional to the galaxies' luminosity. The total burst energy E (provided as an isotropic value) is constant; for a given value of E the observed fluence maps into the burst redshift. We calculate the odds ratio $O_{\rm hg,bg}$ (which is also the likelihood ratio) as a function of E. We want: a) the values of E where $O_{\rm hg,bg} > 1$, indicating the presence of the host galaxies predicted by the model with those values of E; and b) the values of E which maximize $O_{\rm hg,bg}$, indicating the preferred range of E.

Figure 1a shows $O_{\rm hg,bg}$ as a function of E for the Schaefer Compendium. The solid curve includes the k- and e-corrections, while the dashed curve does not. The two curves asymptote to 1 from below. The brightest galaxy in all but one error box (the error box of GRB 781104 has a bright V=15 galaxy) is consistent with the brightest background galaxy expected for an error box of that size. Therefore these boxes can rule out host galaxies of a given brightness, but cannot demonstrate the presence of host galaxy. This does not mean that these error boxes have no significance since they strongly exclude low E values. Figure 1b shows similar curves for the OTs. This database does not exclude low E values as decisively, but indicates that $E > 3 \times 10^{52}$ erg is preferred. These two databases are combined on Figure 1c, which shows that $E \sim 10^{53}$ erg is preferred.

The odds ratios are not dominated by a few error boxes, as demonstrated by Figure 2 which shows the odds ratio by error box for $E = 10^{51}$ erg (asterisks) and $E = 10^{53}$ erg (squares). Boxes 1–23 are the Schaefer Compendium while 24–31 are the OTs. As can be seen, the odds ratios for the Schaefer Compendium are mostly less than 1 for $E = 10^{51}$ erg, except for GRB 781104, and they are very close to 1 for $E = 10^{53}$ erg, even for GRB 781104. The galaxy in GRB 781104's error box is much brighter than L_* for the distance to the burst expected for $E = 10^{53}$ erg, and it falls far out on the Schechter function's exponential; this galaxy is therefore unlikely to be the host for this value of E. On the other hand, the galaxies associated with the OTs are much fainter than the host galaxies expected for $E = 10^{51}$ erg, and thus are more likely to be background galaxies; therefore the odds ratios for these boxes are less than 1. However, for $E = 10^{53}$ erg these observed galaxies are consistent with the predicted host galaxies, and the odds ratios are greater than 1.

Figure 3a shows the $O_{\rm hg,bg}$ curves vs. E for $H_0 = 65$ km s^{-1} Mpc^{-1} instead of $H_0 = 50$ km s^{-1} Mpc^{-1}. Note that the k- and e-corrections still assume $H_0 = 50$ km s^{-1} Mpc^{-1}. As can be seen, this figure barely differs from Figure 1b. On the other hand, Figure 3b shows the same curves if we assume the radius of the error box (in this case the distance between the burst and the galaxy) is $0.5''$ instead of $1''$. In this case the odds ratios are shifted up significantly because the probability that the observed galaxy is an unrelated background galaxy has decreased in proportion to the square of the radius (i.e., the area of the error box) for *each* error box. Nonetheless, the same E range is preferred.

Figure 4 shows the effect of changing the value of M_* by ±1. Increasing M_* means we expect the galaxies to be fainter at a given distance, and therefore the host galaxies can be closer and the bursts can be intrinsically fainter; the opposite is expected if M_* decreases. As can be seen, changing M_* by 1 shifts the energy at which the odds ratio peaks by less than a factor of 2.

4. DISCUSSION

There are now both theoretical and observational arguments that bursts are further and more energetic than predicted by the minimal cosmological model. Theoretically, the source models where the progenitor is a rare endpoint of stellar evolution lead to source evolution models where the burst rate is proportional to the star formation rate (Totani 1997; Wijers et al. 1998; Hartmann & Band 1998). The evolution in the source density balances the cosmological curvature of space, and the intensity distribution is consistent with more distant bursts, although quantitative discrepancies need to be resolved (Petrosian & Lloyd 1998; Hartmann & Band 1998).

The three bursts with redshifts—GRB 970508 at $z = 0.835$ (Metzger et al. 1997; Bloom et al. 1998), GRB 980703 at $z = 0.966$ (Djorgovski et al. 1998a) and GRB 971214 at $z = 3.4$ (Kulkarni et al. 1998)—are further than predicted by the minimal model for their intensities. But currently there are only three redshifts. Similarly, the host galaxies (or upper limits) for the OTs are fainter than expected for the minimal model. Here we have quantified this perception that the host galaxies are faint, and derived the implied standard candle total energy.

However, the burst energy is not a constant for all bursts, as demonstrated by Table 1, and therefore bursts must be characterized by luminosity functions, as we will investigate in a future paper. Nonetheless, our results show that on average the burst energy is significantly greater than previously thought. The theoretical consequences are already being studied.

5. SUMMARY

In Paper I we developed a methodology to determine whether a host galaxy predicted by a specified model is present within a burst error box. This methodology is also applicable to bursts whose positions are known with negligible uncertainty (e.g., bursts followed by OTs) because the relevant error box is the sum of the positional uncertainty and the model-dependent region around the host galaxy in which the burst could have occurred. In Paper I we verified the absence of the host galaxies predicted by the "minimal" model where bursts do not undergo density or luminosity evolution. Here we applied this methodology to two databases, the first a set of 23 moderate-sized error boxes from before 1997, and the second the recent bursts followed by OTs. We used a burst model where bursts occur within $1''$ of the host galaxy and have the same standard candle total energy. We allowed the total burst energy to vary, and found the energy range consistent with the galaxies in the error boxes. To satisfy the observed intensity distribution, the source density must have evolved, as has indeed been suggested.

We found that the pre-1997 error boxes strongly rule out isotropic burst energies below $10^{52.5}$ erg, while the OTs favor energies of $\sim 10^{53}$ erg. This result is relatively insensitive to the value of Hubble's constant and the k- and e-corrections.

In a future study we will consider burst models with luminosity functions. Eventually our host galaxy methodology will be combined with analyses of other data (e.g., the burst intensity distribution) to develop a burst model consistent with all observations.

D. Band's gamma-ray burst research is supported by the *CGRO* guest investigator program and NASA contract NAS8-36081. D. Hartmann acknowledges support from the *CGRO* guest investigator program.

REFERENCES

Band, D. L., & Hartmann, D. H. 1998, ApJ, 493, 555 (Paper I)

Barthelmy, S. D., et al. 1998, in Gamma-Ray Bursts, 4th Huntsville Symposium, AIP Conf. Proc. #428, ed. C. Meegan, R. Preece, and T. Koshut (AIP: Washington), 99

Bloom, J. S., Djorgovski, S. G., Kulkarni, S. R., & Frail, D. A. 1998, ApJ, submitted (astro-ph/9807315)

Brainerd, J. J. 1994, ApJ, 428, 21

Burstein, D., & Heiles, C. 1982, ApJ, 87, 1165

Che, H., Yang, Y., & Nemiroff, R. J. 1998, ApJ, submitted (astro-ph/9810220)

Djorgovski, S. G., Kulkarni, S. R., Bloom, J. S., Goodrich, R., Frail, D. A., Piro, L., & Palazzi, E. 1998a, ApJ, submitted (astro-ph/9808188)

Djorgovski, S. G., et al. 1998b, GCN 41

——— 1998c, GCN 57

——— 1998d, GCN 117

Ellis, R. S. 1983, in The Origin and Evolution of Galaxies, eds. B. J. T. Jones & J. E. Jones (Dordrecht: Reidel), 255

Fenimore, E. E., et al. 1993, Nature, 366, 40

Fenimore, E. E., & Bloom, J. S. 1995, ApJ, 453, 25

Fioc, M., & Rocca-Volmerange, B. 1997, A&A, 326, 950

Fruchter, A. S., et al. 1998, in Gamma-Ray Bursts, 4th Huntsville Symposium, AIP Conf. Proc. #428, ed. C. Meegan, R. Preece, and T. Koshut (AIP: Washington), 509 (astro-ph/9801169)

Galama, T. J., et al. 1998, Nature, 395, 670 (astro-ph/9806175)

Gardner, J. P., Sharples, R. M., Frenk, C. S., & Carrasco, B. E. 1997, ApJ, 480, L99

Hartmann, D. H., & Band, D. L. 1998, in Gamma-Ray Bursts, 4th Huntsville Symposium, AIP Conf. Proc. #428, ed. C. Meegan, R. Preece, and T. Koshut (AIP: Washington), 615

Hogg, D. H., & Fruchter, A. S. 1998, ApJ, submitted (astro-ph/9807262)

Jones, L. R., Fong, R., Shanks, T., Ellis, R. S., & Peterson, B. A. 1991, MNRAS, 249, 481

Koo, D. C., & Kron, R. G. 1992, ARAA, 30, 613

Krumholtz, M., Thorsett, S. E., & Harrison, F. A., et al. 1998, ApJ, 506, L81

Kulkarni, S., et al. 1998, Nature, 393, 35

Larson, S. B. & McLean, I. S. 1997, ApJ, 491, 93

Leitherer, C., et al. 1996, PASP, 108, 996 (including tables on AAS CD-ROM series, Vol. 7)

Lin, H., Kirshner, R. P., Shectman, S. A., Landy, S. D., Oemler, A., Tucker, D. L., & Schechter, P. L. 1996, ApJ, 464, 143

Mattig, W. 1958, Astr. Nachr., 284, 109

Meegan, C., et al. 1998, BATSE catalog, http://www.batse.msfc.nasa.gov/data/grb/catalog/

Metzger, M. R., et al. 1997, Nature, 387, 878

Palmer, D., et al. 1998, in Gamma-Ray Bursts, 4th Huntsville Symposium, AIP Conf. Proc. #428, ed. C. Meegan, R. Preece and T. Koshut (AIP: Washington), 304 (astro-ph/980204)

Peebles, P. J. E. 1993, Principles of Physical Cosmology (Princeton: Princeton University Press)

Petrosian, V., & Lloyd, N. M. 1998, in Gamma-Ray Bursts, 4th Huntsville Symposium, AIP Conf. Proc. #428, ed. C. Meegan, R. Preece and T. Koshut (AIP: Washington), 35

Ratcliffe, A., Shanks, T., Parker, Q. A., & Fong, R. 1997, MNRAS, submitted

Schaefer, B. E. 1992 in Gamma-Ray Bursts: Observations, Analyses and Theories, ed. C. Ho, R. I. Epstein, & E. E. Fenimore (Cambridge: Cambridge Univ. Press), 107

——— 1998, ApJ, submitted (astro-ph/9810424)

Schaefer, B. E., Cline, T. L., Hurley, K. C., & Laros, J. G. 1998, ApJS, 118, 353.

Smail, I., Hogg, D. W., Yan, L., & Cohen, J. G. 1995, ApJ, 449, L105

Totani, T. 1997, ApJ, 486, L71

Wijers, R.A.M.J., et al. 1998, MNRAS, 294, L13

Woods, P., Kippen, R. M., & Connaughton, V. 1998, GCN 112

This preprint was prepared with the AAS LaTeX macros v4.0.

Fig. 1.— The odds ratio $O_{\rm hg,bg}$ as a function of the standard candle burst energy E (assumed to have been radiated isotropically). The solid curve includes k- and e-corrections whereas the dashed curve does not. The assumed cosmological model is $H_0 = 50$ km s^{-1} Mpc^{-1}, $\Omega_0 = 0.1$ and $\Lambda_0 = 0$. Panel 1a uses the pre-1997 bursts from Schaefer et al. (1998), 1b uses the recent bursts followed by optical transients, and 1c uses both databases. $O_{\rm hg,bg} \ll 1$ indicates the absence of the host galaxy predicted by the model with the given value of E, while a maximum value of $O_{\rm hg,bg}$ shows the most likely value of E.

Fig. 2.— Distribution of the odds ratio $O_{\rm hg,bg}$ by burst for $E = 10^{51}$ erg (asterisks) and $E = 10^{53}$ erg (squares). Bursts 1–23 are the pre-1997 bursts from Schaefer et al. (1998): 1. GRB 781104; 2. GRB 781119; 3. GRB 781124; 4. GRB 790113; 5. GRB 790307; 6. GRB 790313; 7. GRB 790325; 8. GRB 790329; 9. GRB 790331; 10. GRB 790406; 11. GRB 790418; 12. GRB 790613; 13. GRB 791105; 14. GRB 791116; 15. GRB 910122; 16. GRB 910219; 17. GRB 911118; 18. GRB 920325; 19. GRB 920406; 20. GRB 920501; 21. GRB 920711; 22. GRB 920720; and 23. GRB 920723. Bursts 24–31 are the recent bursts followed by an optical transient: 24. GRB 970228; 25. GRB 970508; 26. GRB 971214; 27. GRB 980326; 28. GRB 980329; 29. GRB 980519; 30. GRB 980613; and 31. GRB 980703.

Fig. 3.— The same as figure 1b except in panel 3a a value of $H_0 = 65$ km s^{-1} Mpc^{-1} is used, while in panel 3b the radius of the error box surrounding the burst is decreased by a factor of 2.

Fig. 4.— The dependence of the odds ratio on the value of M_*. M_* has been increased (dashed curve) or decreased (dot-dashed curve) by 1 compared to the currently accepted value (solid curve). The calculation assumes $H_0 = 50$ km s^{-1} Mpc^{-1}, $\Omega_0 = 0.1$ and $\Lambda_0 = 0$, and the $k-$ and $e-$corrections are included.

Table 1. Energies of Bursts with Redshifts

Burst	z	Ref.	Fluence[a]	Peak Flux[b]	Energy [c]
GRB 970508	0.835	d	3.96×10^{-6}	0.97	6.50×10^{51}
GRB 971214	3.42	e	1.09×10^{-5}	1.95	2.95×10^{53}
GRB 980425	8.43×10^{-3}	f	4×10^{-6}	0.96	7.24×10^{47}
GRB 980703	0.966	g	4.59×10^{-5}	2.42	1.03×10^{53}

[a]Fluence greater than 25 keV, erg cm^{-2}, assumed to be bolometric. From the BATSE catalog—Meegan et al. (1998).

[b]Peak photon flux in the 50–300 keV band accumulated over 1.024 s. From the BATSE catalog—Meegan et al. (1998).

[c]Total burst energy if radiated isotropically. Assumes $H_0 = 65$ km s^{-1} Mpc^{-1}, $\Omega = 0.3$, and $\Lambda = 0$.

[d]Metzger et al. (1997); Bloom et al. (1998).

[e]Kulkarni et al. (1998).

[f]Galama et al. (1998).

[g]Djorgovski et al. (1998a).

Table 2. The Host Galaxies Associated with Optical Transients

Burst	Fluence[a]	$R_{\rm det}$[b]	Ref.	Ext.[c]	$R_{\rm corr}$
GRB 970228	4.6×10^{-6}[d]	25.2	e	0.65	24.6
GRB 970508	3.96×10^{-6}	25.72	f	0.17	25.55
GRB 971214	1.09×10^{-5}	25.6	g	0.01	25.6
GRB 980326	1×10^{-6}	25.5	h	0.20	25.3
GRB 980329	8.26×10^{-5}	25.7	i	0.31	25.4
GRB 980519	2.54×10^{-5}	25.55	j	0.85	24.7
GRB 980613	1.71×10^{-6}[k]	24.5	l	0.07	24.4
GRB 980703	4.59×10^{-5}	22.3	m	0.14[m]	22.2

[a]Fluence greater than 25 keV, erg cm^{-2}, from the BATSE catalog (Meegan et al. 1998), unless otherwise indicated.

[b]R magnitude of detected galaxy.

[c]Extinction from Burstein & Heiles (1982) quoted by Hogg & Fruchter (1998), unless otherwise indicated.

[d]Palmer et al. (1998).

[e]HST observation of extended source reported by Fruchter et al. (1998).

[f]Galaxy at $z = 0.835$ observed by Bloom et al. (1998).

[g]Extended source observed by Kulkarni et al. (1998) with $z = 3.418$.

[h]Galaxy observed by Djorgovski et al. (1998b), GCN 57.

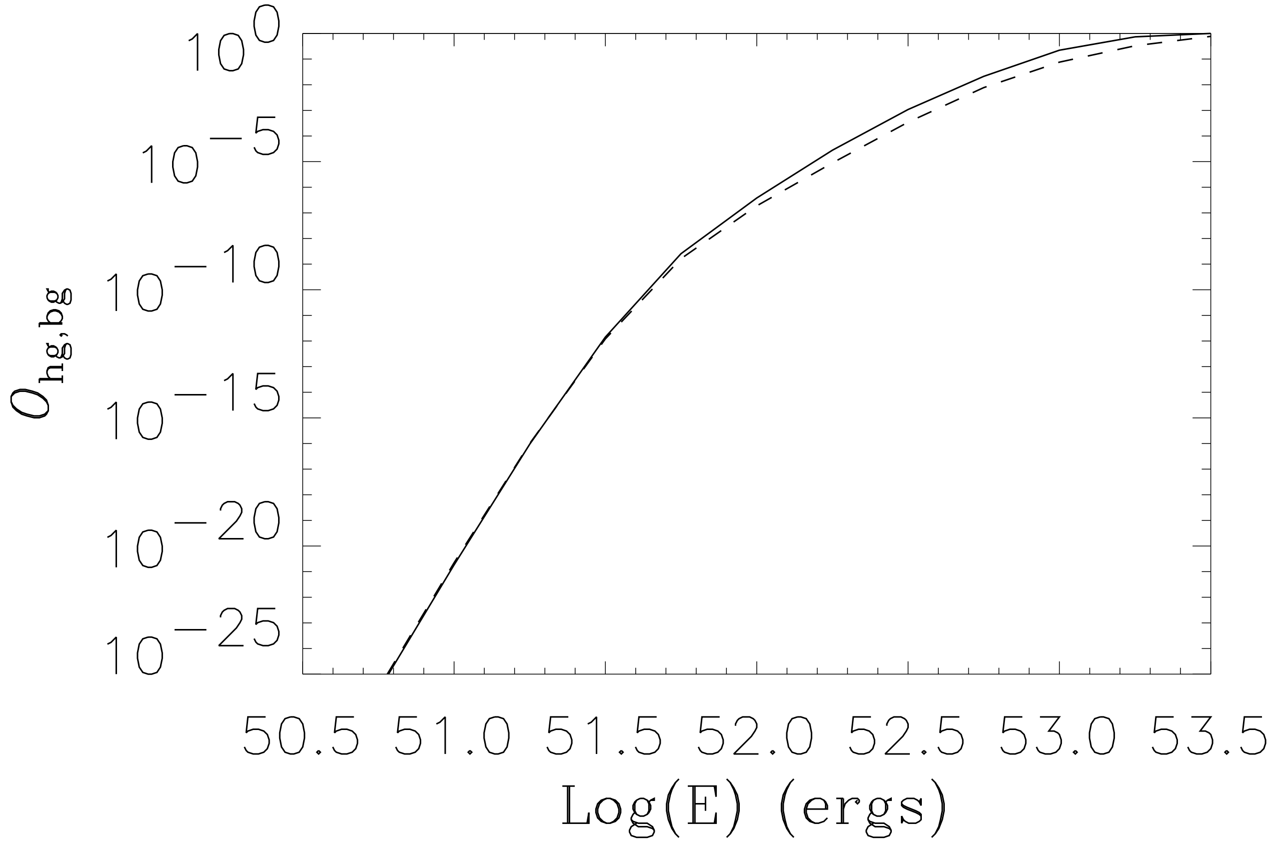
[i]Galaxy observed by Djorgovski et al. (1998c), GCN 41.

[j]H. Pedersen quoted by Hogg & Fruchter (1998).

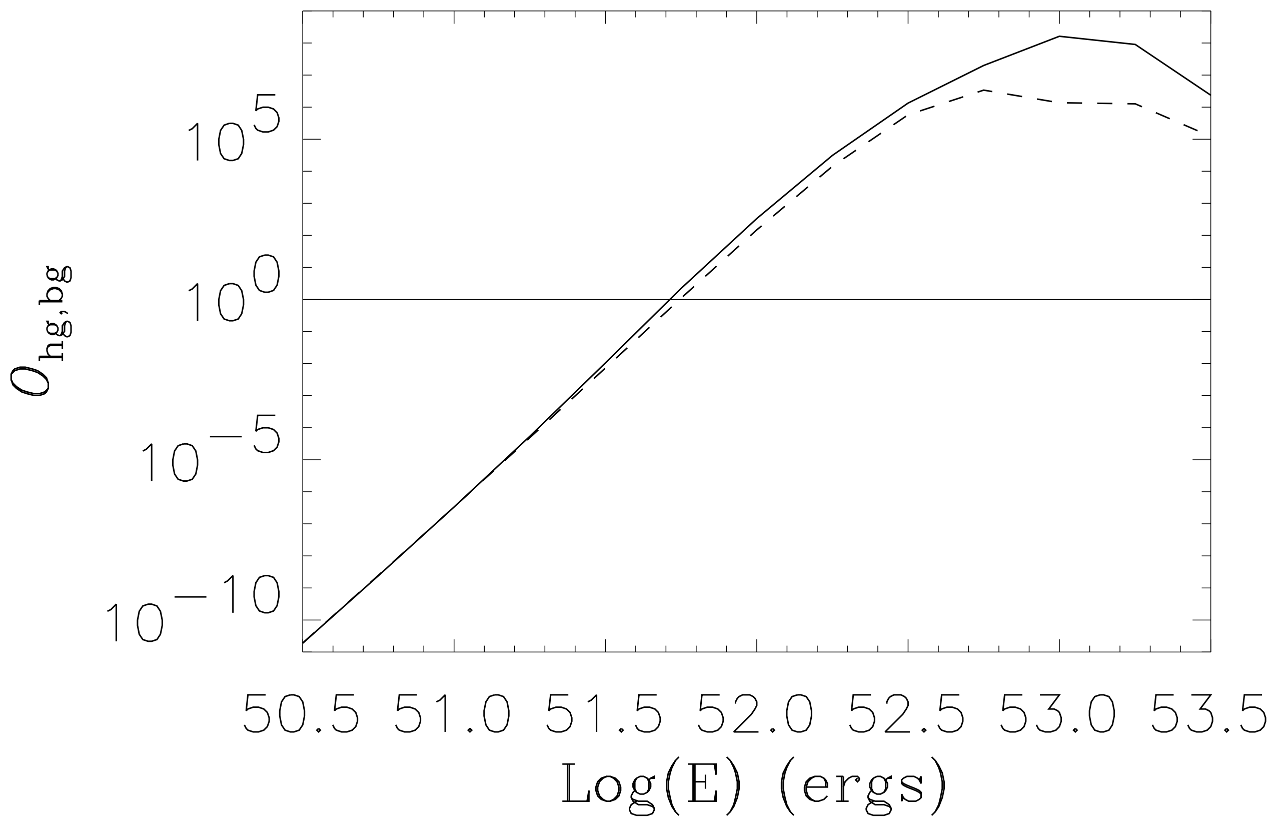
[k]Woods et al. (1998), GCN 112.

[l]Djorgovski et al. (1998d), GCN 117.

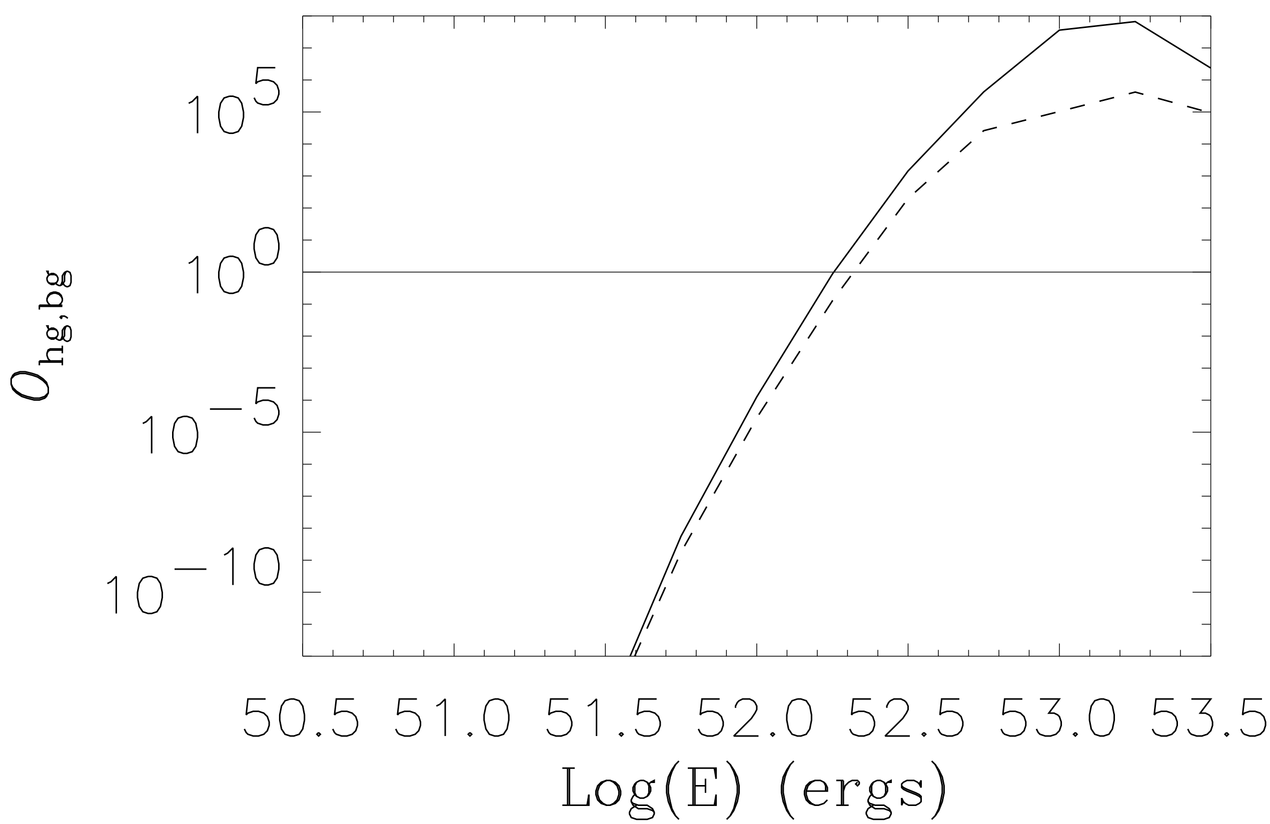
[m]Djorgovski et al. (1998a).



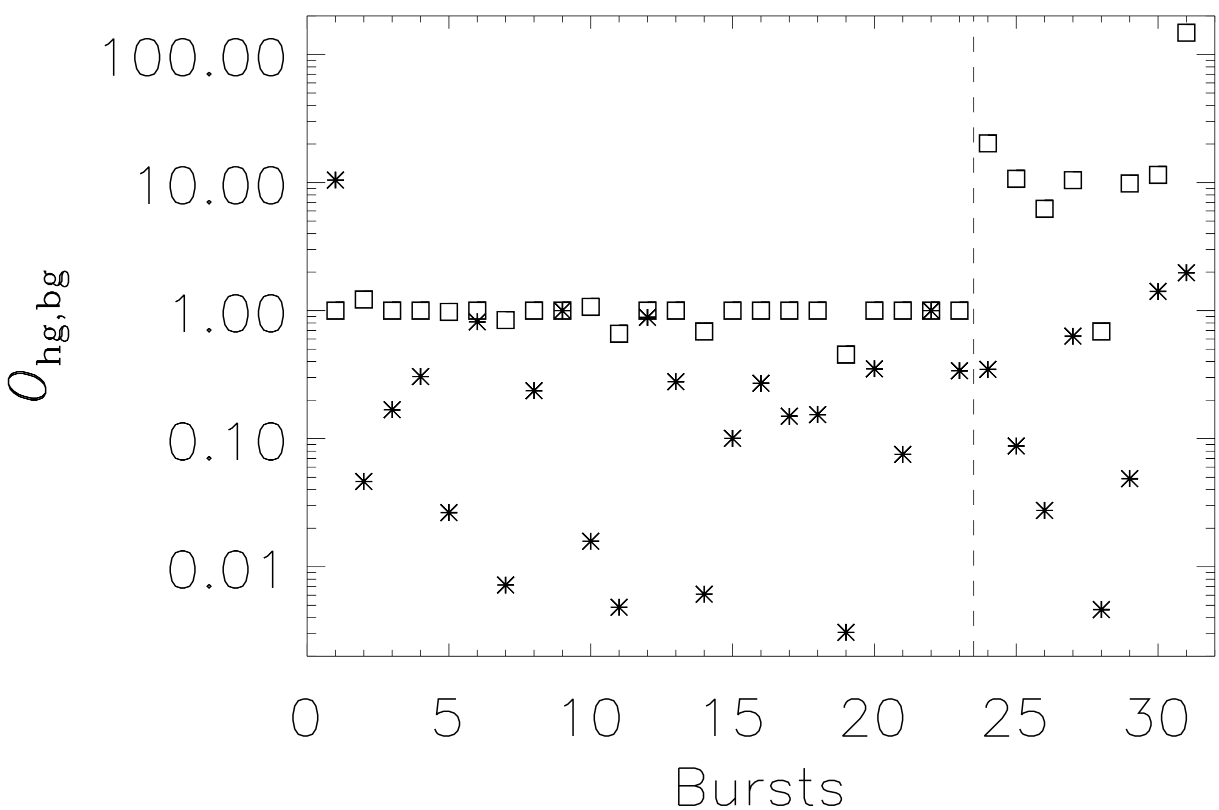
10^{0}
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
$O_{\mathrm{hg,bg}}$
50.5
51.0
51.5
52.0
52.5
53.0
53.5
Log(E) (ergs)



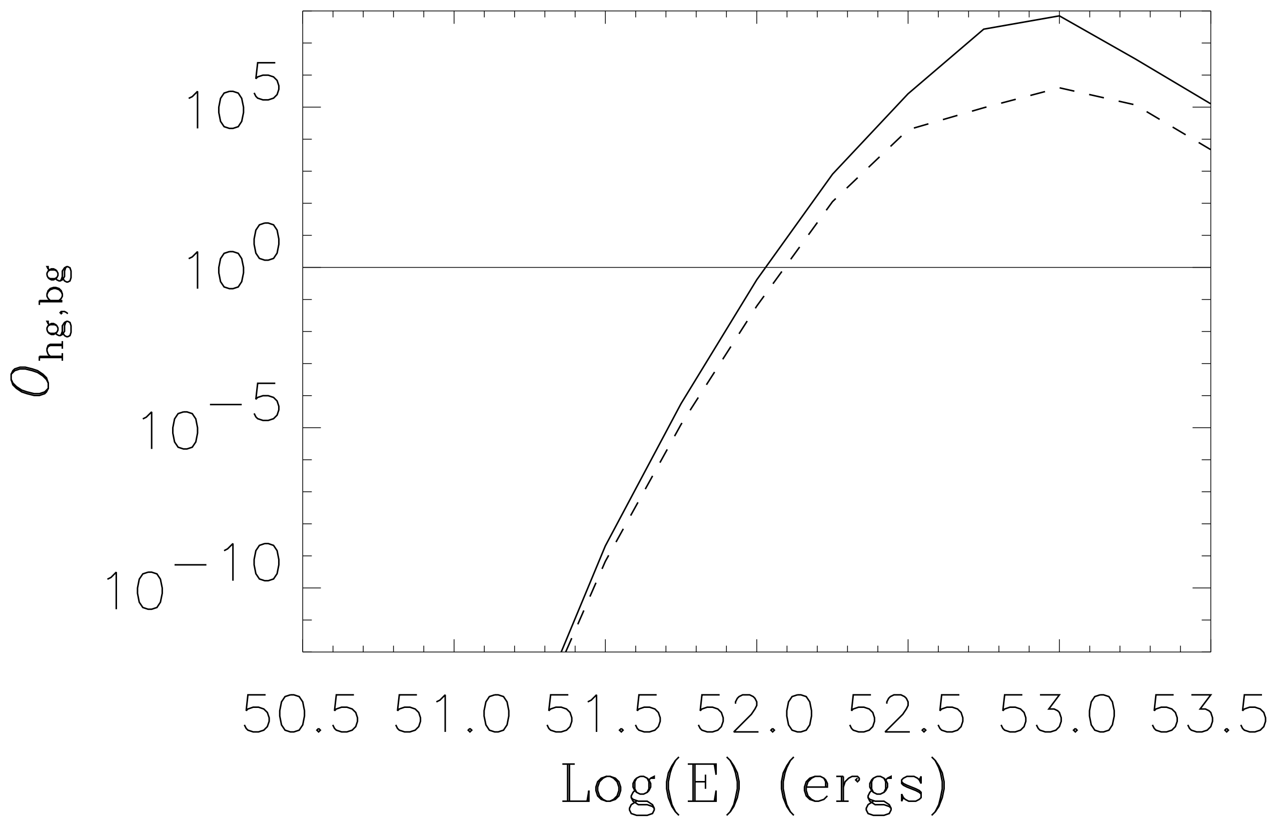
10^{5}
10^{0}
10^{-5}
10^{-10}
$O_{\rm hg,bg}$
50.5
51.0
51.5
52.0
52.5
53.0
53.5
Log(E) (ergs)



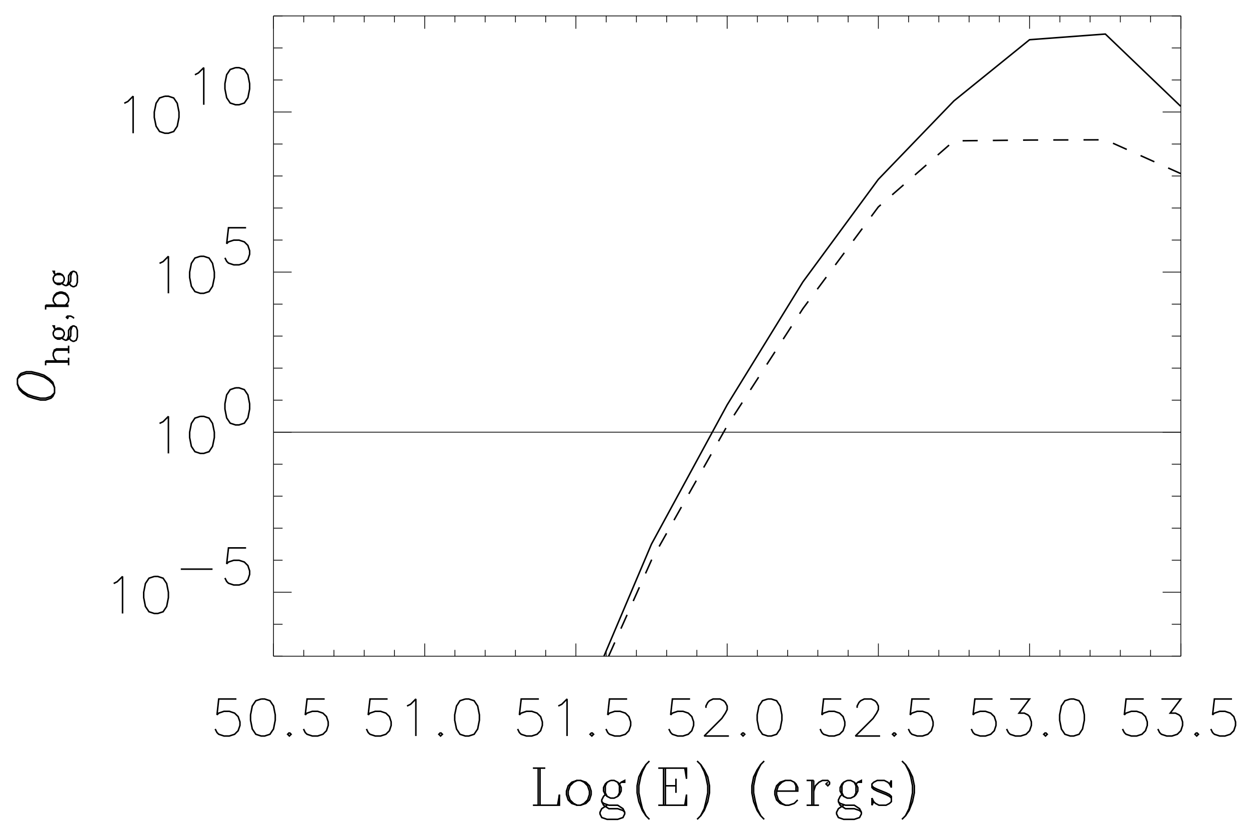
$O_{\rm hg,bg}$
10^5
10^0
10^{-5}
10^{-10}
50.5 51.0 51.5 52.0 52.5 53.0 53.5
Log(E) (ergs)



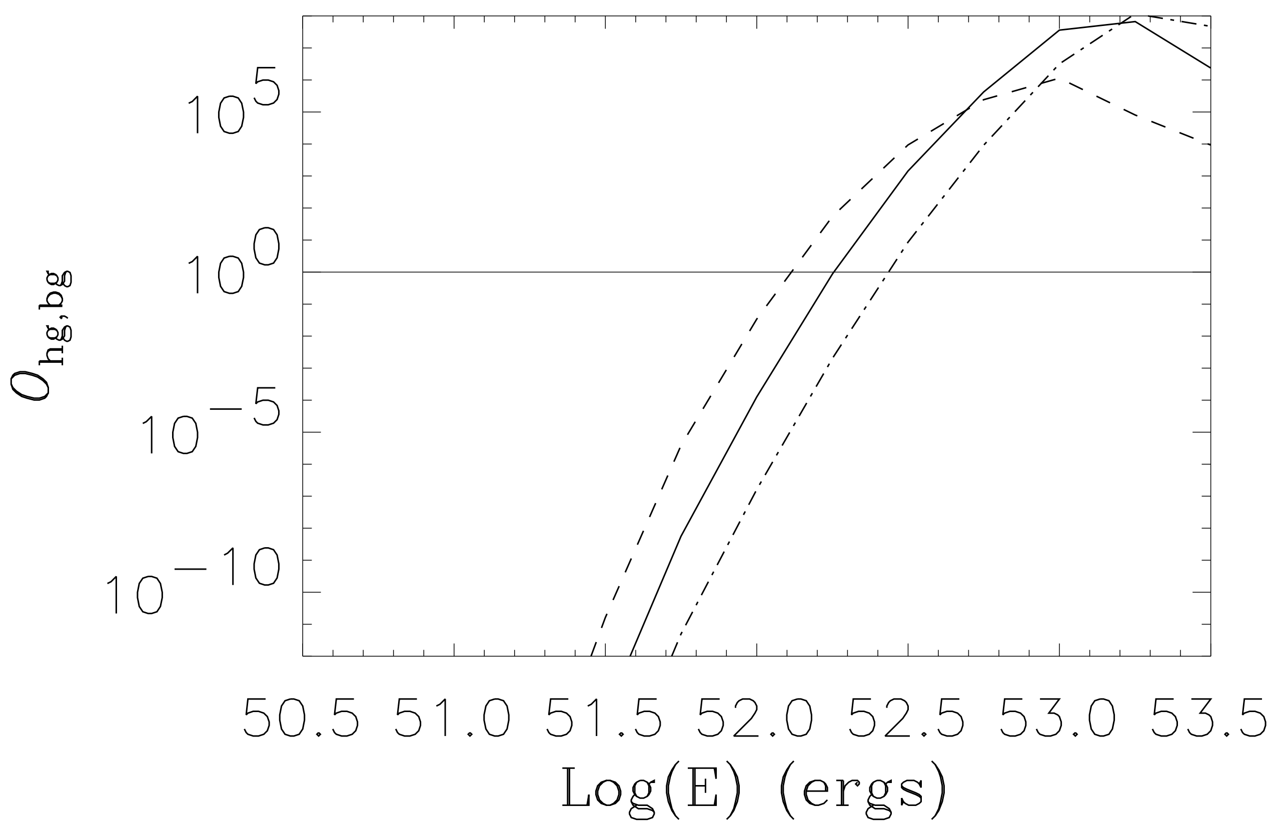
100.00
10.00
1.00
0.10
0.01
$O_{\mathrm{hg,bg}}$
0
5
10
15
20
25
30
Bursts



10^5
10^0
10^{-5}
10^{-10}
$O_{\rm hg,bg}$
50.5 51.0 51.5 52.0 52.5 53.0 53.5
Log(E) (ergs)



$O_{\rm hg,bg}$
10^{10}
10^{5}
10^{0}
10^{-5}
50.5
51.0
51.5
52.0
52.5
53.0
53.5
Log(E) (ergs)


10^5
10^0
10^{-5}
10^{-10}
$O_{\rm hg,bg}$
50.5 51.0 51.5 52.0 52.5 53.0 53.5
Log(E) (ergs)